Diesel Particulate Filtration Technology in Underground Mines

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Diesel engines play important role in underground mining.

- Underground miners in the U.S.A.(2007):
  - ~ 43,000 miners in 616 underground coal mines;
  - ~ 12,600 miners in 240 underground metal/nonmetal mines.

- U.S.A.:
  - ~ 4,300 diesel powered equipment in 160 underground coal mines, and
  - ~ 4,000 diesel powered equipment in 240 underground metal and nonmetal mines.

- Ontario, Canada:
  - ~ 2,000 diesel powered equipment in 29 underground metal and nonmetal mines.

Underground mining fleets are characterized with wide variety of applications.

- Heavy-duty equipment: Load-haul-dump (LHD) vehicles and haulage trucks, shield haulers, etc.
- Light-duty equipment: bolters, forklifts, fuel & lub trucks, personnel carriers, scissor lifts, etc.





Light-duty vehicles make app. 60-70 percent of underground mining fleets.

- **Arch Minerals (Forbush, 2008):**
  - 4 UG coal mines in Utah and Colorado);
  - Total of 496 diesel-powered units;
  - 186 heavy-duty production units;
  - 310 light-duty utility units.
- **Stillwater Mining Company (Collins, 2008):**
  - Nye Mine, platinum & palladium UG mine, Montana;
  - Total of 330 diesel-powered units;
  - 134 heavy-duty production units;
  - 196 light-duty utility units.
- **Ontario, Canada (MLRC Diesel Subcommittee, 2002):**
  - Total of ~2000 diesel-powered units;
  - ~600 heavy-duty production units;
  - -1400 light-duty utility vehicles.

Since January 2001 exposure of miners to diesel particulate matter (DPM) in U.S. underground mines is regulated.

- In general underground miners are exposed to concentrations of diesel particulate matter (DPM) that are significantly higher then those of any other occupation.

- Mine Safety and Health Administration (MSHA) regulations limit exposure of underground miners to DPM
  - **Underground metal and nonmetal mines:**
    - 30 CFR Part 57.5060 - Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners (January 2001);
    - 160_{TC} µg/m^3 PEL (effective May 20, 2008);
    - **Personal exposure limit, performance rule**.
  - **Underground coal mines:**
    - 30 CFR Part 72 - Diesel Particulate Matter Exposure of Underground Coal Miners (January 2001);
    - Heavy-duty (permissible and nonpermissible) should emit less then 2.5 g/hr;
    - Light-duty should emit less then 5 g/hr.
    - **Emissions standard, prescribed solution.**

Exposure of underground miners to noxious gases emitted by diesel engines is also regulated.

- **Underground metal and nonmetal**

  30 CFR 57.5001. Safety and Health Standards Underground for Metal and Nonmetal Mines. Exposure Limits for Airborne Contaminants:

  - carbon dioxide (CO_2), ACGIH TLV-TWA is 5000 ppm;
  - carbon monoxide (CO), ACGIH TLV-TWA is 50 ppm;
  - **nitric oxide (NO), ACGIH TLV-TWA is 25 ppm;**
  - **nitrogen dioxide (NO_2), ACGIH TLV-TWA is 3 ppm, ACGIH TLV-STEL (ceiling limit) is 5 ppm.**

  NOTE: MSHA adopted 1973 ACGIH standards.

- **Underground coal mines**

  30 CFR § 70.1900. Coal Mine Safety and Health. Exhaust Gas Monitoring (1994).

  - carbon monoxide (CO), ACGIH TLV-TWA is 50 ppm;
  - **nitrogen dioxide (NO_2), ACGIH TLV-TWA is 3 ppm, ACGIH TLV-STEL (ceiling limit) is 5 ppm.**

  NOTE: MSHA adopted 1972 ACGIH standards.

Reducing diesel emissions and exposure of underground miners to diesel particulate matter and gases presents special challenge.

- Challenging business;
- Rugged environment;
- Wide variety of applications;
- Confined space with limited ventilation;
- Elevations between 10,000 ft below and 14,000 ft above see level;
- Occupational regulations (NO and NO_2 vs. NO_x);
- Underground coal mining permissible applications:
  - Surface temperature control;
  - Exhaust temperature control;
  - Intrinsically safe engine.
- High requirements vs. relatively small market

Reducing exposure of underground miners to diesel particulate matter and gases requires multifaceted integrated approach with well established hierarchy of solutions involving:

- Control of diesel emissions at their source:
  - Engine-out emissions;
  - Aftertreatment technologies.
- Control of airborne pollutants:
  - Ventilation;
  - Environmental cabs;
  - Personal protective equipment.
- Institution of administrative controls:
  - Better utilization and management of available resources;
  - No idling policy…

The major component of successful approach is controlling diesel emissions at their source

- Reduction of engine-out emissions through:
  - Utilization of contemporary diesel engine technology;
  - Implementation of emissions assisted maintenance programs;
  - Utilization of alternative fuels.
- Aftertreatment technologies:
  - Retrofit applications;
  - OEM applications.

Wide variety of diesel engines are currently deployed in underground mining industry

- MSHA approves engines for underground coal mining industry;
- Underground metal non metal industry can use MSHA or EPA approved engines;
- Tier 0, Tier 1, Tier 2 and are widely present.
- Regulations for coal mining require that all newly introduced engines are Tier 3:
  - NO_x vs. DPM

Wide variety of diesel engines are currently deployed in underground mining industry

- Tier 4 engines should have integrated advanced exhaust aftertreatment systems:
  - Diesel particulate filter systems and NO_x absorbers.
  - Are Tier 4 engines going to provide all answers?
    - NO_2 slip;
    - NH_3 slip…

The emission-assisted maintenance is perceived as important tool in hierarchy of solutions.

- Emission-assisted maintenance vs. repair facility:
  - Emissions are used as diagnostic tools;
  - 250 hr PM;
  - Develop in house expertise;
  - Establish baseline and own criteria;
  - Prompt action...
- The objective is to establish engine specific baseline and maintain emissions at “new” (baseline) level.
- In-use emissions vs. certification emissions.

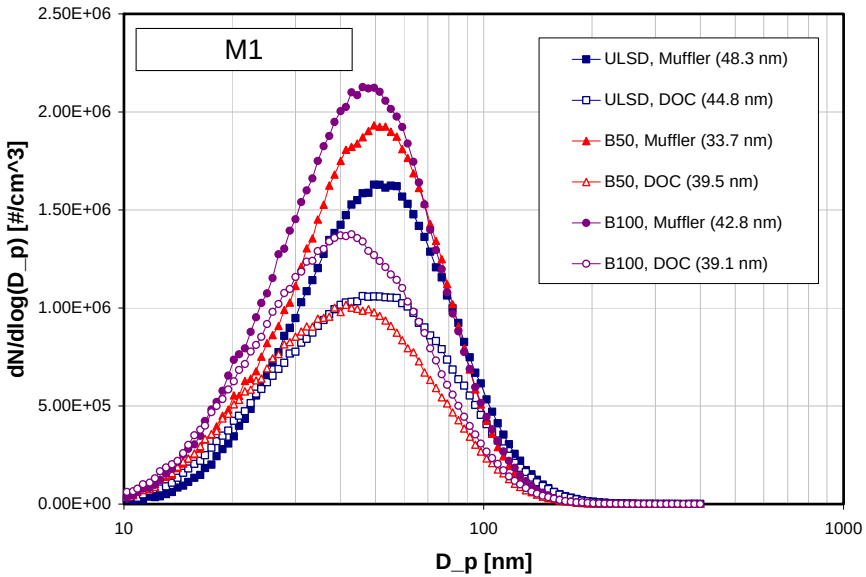
The potential of alternative fuel formulations to reduced exposures is explored

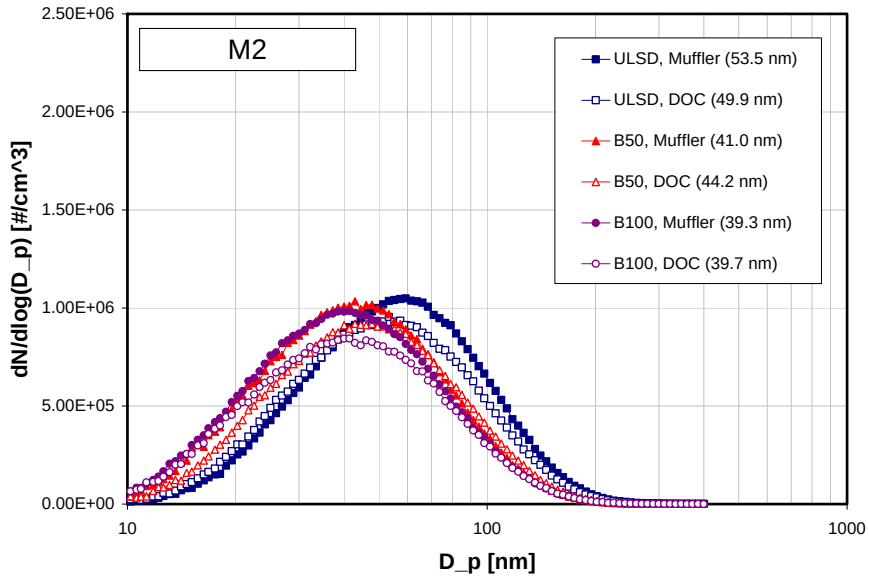
- Biodiesel is the alternative fuel of choice.
- Biodiesel is typically blended with ULS diesel fuel
  - B50
  - Engine warranty issues
- Cost, availability, fuel supply management, engine compatibility, maintenance, potential loss of engine power and efficiency, secondary emissions are some of the issues related to use of biodiesel.
- Compatibility with DPF systems.

Implementation of aftertreatment technologies is perceived as important tool in reducing exposures.

- **Current Trends (DOC OEM and DPFs retrofit)**
  - Diesel oxidation catalytic converters (DOCs) for CO and HC;
  - Flow trough filter (FTF) systems
  - Diesel particulate filter (DPF) systems;
  - Filtration systems (FS) with disposable filter elements (DFE).
- **Future (OEM and retrofit, pending engine and aftertreatment technology development)**
  - DOC
  - DPF or FTF systems
  - Selective catalyst reduction (SCR)

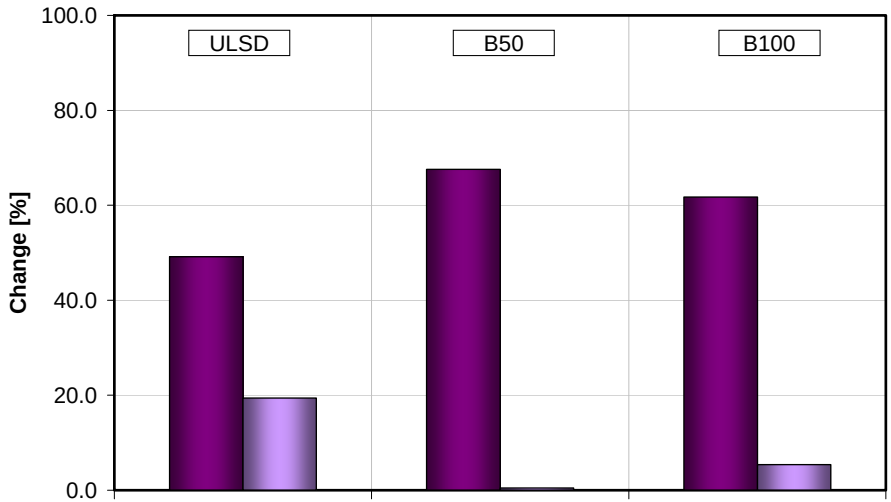
The effects of DOCs on aerosols are function of exhaust temperature.





M1, moderate exhaust temperature

Change in total particulate mass concentrations for M1 and M2



M2, relatively high exhaust temperature

MSHA verify DPM control technologies.

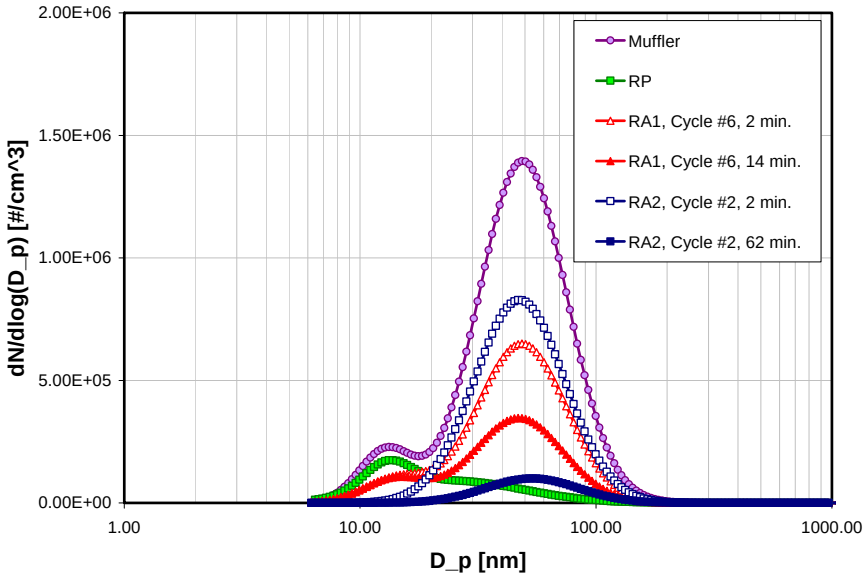
- The list of verified products and adopted efficiency values is available at

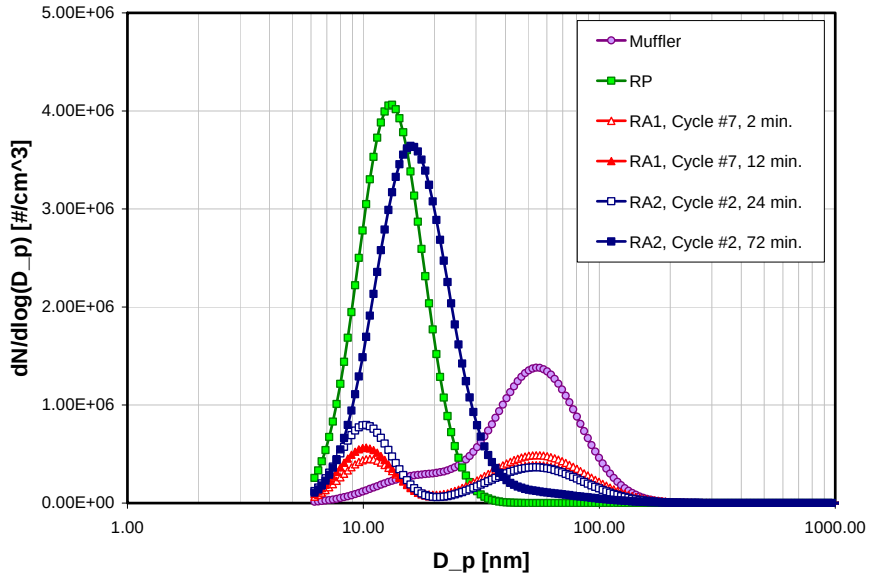
  http://www.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf

  - Diesel particulate filter (DPF) systems
  - Disposable filter elements (DFE)

Filtration System	Efficiency (TDPM)
Cordierite DPF	85%
Silicon carbide DPF	87%
Sintered metal DPF	80-81%
DFE	80-95%

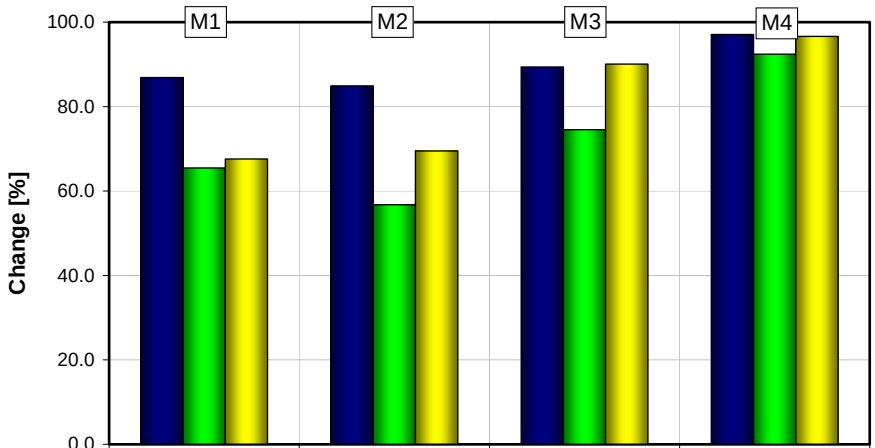
The effects of DPFs on aerosols are function of exhaust temperature.





M1, moderate exhaust temperature

Change in total particulate number concentrations for different regeneration strategies



	M1	M2	M3	M4
RP	86.8	84.9	89.4	97.1
RA1	65.5	56.7	74.5	92.4
RA2	67.6	69.5	90.0	96.6

Mode

M2, relatively high exhaust temperature

A number of DPF systems were long- and short-term evaluated in Canadian and U.S. mines.

Diesel Emissions Evaluation Program (DEEP, http://www.deep.org/research.html)

- Field evaluation of diesel particulate filter systems in an underground mine – INCO (2001-2004):
  - Five heavy-duty
    - Two passive systems;
    - Two active (on-board electrical) system;
    - One active (on-board, fuel burner) system;
    - One passive (fuel borne additive)/active (on-board electrical) system
  - Four light-duty
    - Two active (on-board electrical);
    - One active (off-board electrical)

A number of DPF systems were long- and short-term evaluated in Canadian and U.S. mines.

Diesel Emissions Evaluation Program (DEEP)
http://www.deep.org/research.html

- Field evaluation of diesel filter systems in an underground mine - Noranda Technology Centre (2000-2003):
  - Four heavy-duty
    - One passive system (base metal catalyst)
    - Two passive system (Fe/Sr fuel additive)
    - One passive (Pt catalyst)/Active (on-board electrical)

NIOSH short-term evaluated several aftertreatment technologies and alternative fuels at Stillwater Nye Mine

National Institute for Occupational Safety and Health (NIOSH)
http://www.cdc.gov/niosh/mining/pubs/programareapubs8.htm

- Effectiveness of selected diesel particulate matter control technologies for underground mining applications.
  - Isolated Zone Study, 2003
    - One passive systems with Pt washcoat;
    - One passive systems with base metal washcoat;
    - One passive system with Pt washcoat and Pt/Ce fuel borne catalyst;
    - One active system with on-board electrical regeneration;
    - One filtration system with DFE.
  - Isolated Zone Study, 2004
    - One active system with on-board diesel fuel burner;
    - One filtration system with two different types of DFEs.
    - One FTF

DPF and DFE Systems in Underground Coal Mining

(Source: MSHA) https://lakegovprod2.msha.gov/DieselInventory/ViewDieselInventoryExternal.aspx

- DPF and DFE technology is silently inching its way into underground coal mines

- Inventory of DPF and DFE systems shows:
  - ~1320 vehicles equipped with filtration systems;
  - ~ 800 filtration systems with DFEs (heavy-duty permissible and non-permissible);
  - ~ 520 DPF systems (heavy- and light-duty non-permissible);
  - 1 FTF.

Filtration systems with DFEs are used on heavy-duty permissible vehicles for more then decade.

- Filtration systems with DFEs are using water jacketing and wet (water-to-air) or dry (air-to-air) heat exchangers to keep surface and exhaust temperatures below limits.
- Paper and synthetic DFEs are used to filter cooled exhaust.

Simplified filtration systems with DFEs are used on heavy-duty non-permissible vehicles for past couple years.

- Filtration systems with DFE for non-permissible applications are using dry heat exchangers to keep exhaust temperatures below 650 F.
- Synthetic material DFE are used to filter cooled exhaust.

Some of the underground metal and nonmetal mines are proactive in using DPF technology.

- Stillwater Mining Company (Nye Mine, platinum & palladium UG mine, Montana):
  - Total of ~ 330 diesel-powered units;
  - ~ 85 DPF systems;
  - ~ 160 FTF systems;
  - ~ 60 DOC.

- Aftertreatment systems on heavy-duty fleet units:
  - 20 precious metal catalyzed passive systems on 10-ton haulage trucks
  - 4 precious metal catalyzed passive systems on locomotives
  - 4 base metal catalyzed passive DPF systems on CAT AD30 haulage trucks
  - 44 passive precious metal catalyzed systems on 2 yd^3 LHD vehicles
  - 2 active systems with on-board electrical regeneration partially regenerated using fuel borne catalyst on 1½ yd^3 LHD vehicles;
  - 36 FTFs

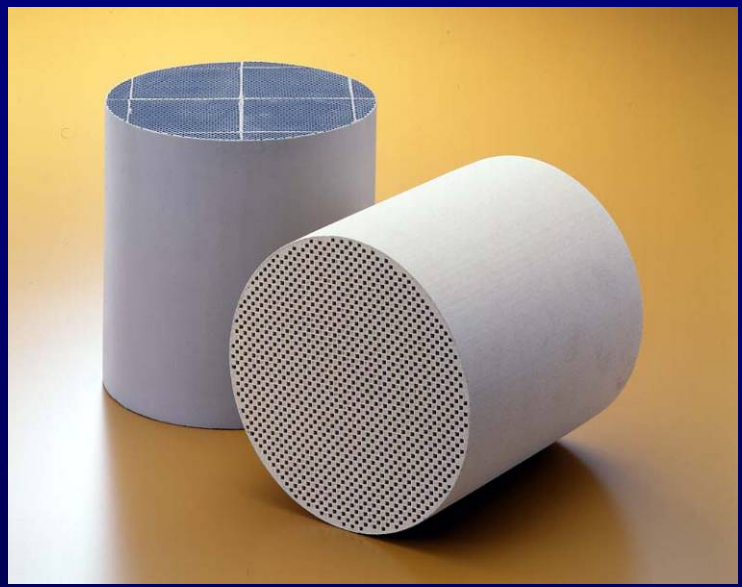
- Aftertreatment systems on light-duty fleet units:
  - 5 active systems with off-board electrical regeneration
  - 3 passive systems with NO_2 suppressing catalyst
  - 124 FTFs

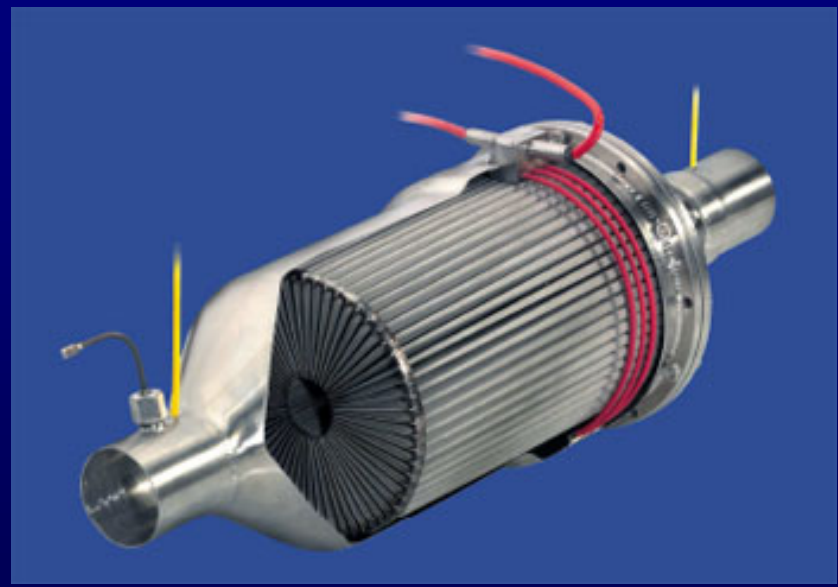
DPF systems in Canadian underground metal and nonmetal mining are relatively sparse.

- Total of ~5000 diesel-powered units.
- ~20 vehicles are retrofitted with DPF systems:
  - 18 systems at Xstrata Zink Brunswick Mine, New Brunswick:
    - passive systems with wash-coated base metal catalyst;
  - 2 systems at Vale Inco Creighton Mine, Sudbury:
    - active systems with on-board electrical regeneration fully or partially regenerated using fuel borne catalyst

The ceramic monolith elements dominate underground mining DPF market in the U.S.A.

- Wall flow monoliths
  - Cordierite
  - Silicon Carbide (SiC)
- Sintered metal filters





The concern over NO_2 "slip" influenced selection of regeneration strategy for DPF systems for coal mining applications:

- MSHA advise against using platinum catalyzed passive DPF system in underground coal mines due to potential for increase in NO_2 emissions.

- The popular choices of DPF systems in coal mining:
  - Passive systems regenerated with help of platinum/cerium fuel born catalyst;
  - Passive systems with wash-coated base metal catalyst;
  - Passive systems with wash-coated NO_2 suppressing catalyst;
  - Active systems with on-board electrical regeneration;
  - Active systems with off-board electrical regeneration.

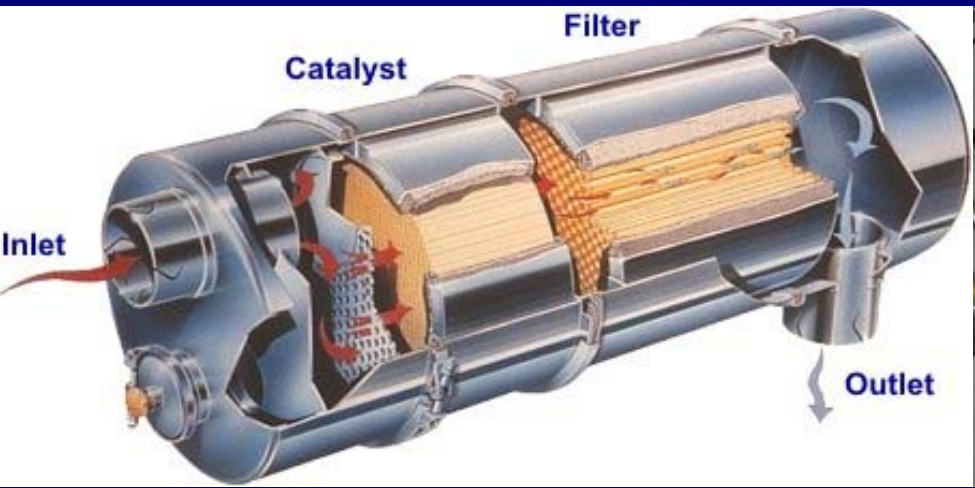
Secondary emissions of NO_2 are major road block for implementation of passive DPF systems in underground mines.

- Effects of the aftertreatment system on NO_2 emissions is function of:
  - catalyst formulation;
  - exhaust temperatures;
  - NO_x to PM ratio in the engine-out exhaust;
  - amount of soot in DPF system;
  - fuel sulfur content…

- Several studies showed that the systems with wash-coated platinum based catalysts promote NO to NO_2 conversion at the temperatures needed for DPF regeneration.

Concern over NO_2 slip delayed implementation of CRT type DPF systems in underground mines.

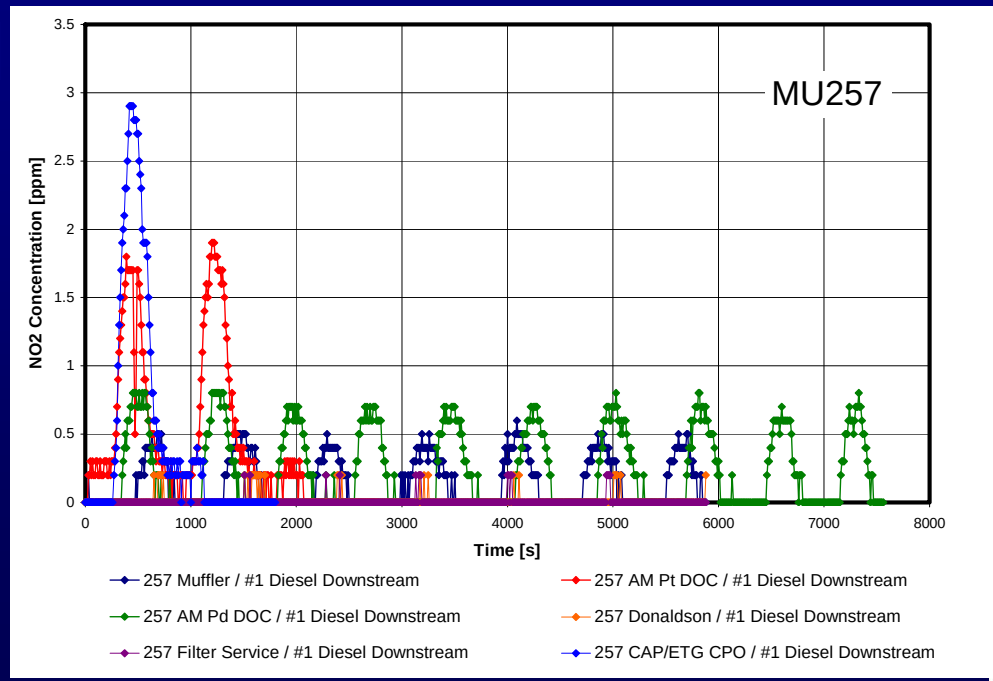
- The pre-filter with Pt catalyst is used to convert most of NO into NO_2. As a strong oxidizer NO_2 is used to regenerate DPF.
- The major challenge is balancing NO_2 production and consumption over real life cycle.
- Hydrocarbon injection and reaction over the catalyst was explored.
- Similar system will be soon installed and evaluated in Canadian underground metal mine.



The NO to NO_2 conversion was observed for certain conditions for some types of DOC.

- DOCs are frequently used at the outlet of DPF system that are actively regenerated. During one of the isolated zone studies at Stillwater Nye Mine, two DOCs with two types of catalyst formulations, installed at the outlet of diesel fuel burner regenerated DPF system were evaluated:
  - The use of the DOC with Pt formulation resulted in significantly elevated NO_2 concentrations in mine air.
  - The DOC with Pd formulation slightly elevated NO_2 concentrations.

DPF system with diesel fuel burner and DOC



Not all catalyzed DPF systems promote NO to NO_2 conversion.

- Some data indicate that base metal wash-coated catalysts did not exhibit tendency to increase NO_2 emissions.
- The systems using fuel borne catalysts, even those that are based on platinum, were not found to increase significantly NO_2 emissions.
- The reaction between NO_2 and DPM in uncatalyzed filters my result is slight reduction in overall NO_2 concentrations.
- New formulations with NO_2 suppressant are marketed for underground mining industry.

Implementation of retrofit aftertreatment systems on underground mining equipment proved to be challenge.

- Hierarchy of strategies should he established and adequately instituted prior to implementation of DPF technology.
- Selection of adequate DPF system for the application requires thorough consideration.
- DPF regeneration is important design factor.
- Optimization of the systems for every single underground mining applications is needed.
- Only well designed installation, thorough execution, and religious maintenance warranty success.
- Operator education proved to be critical for success.

Thank you for your attention!!!

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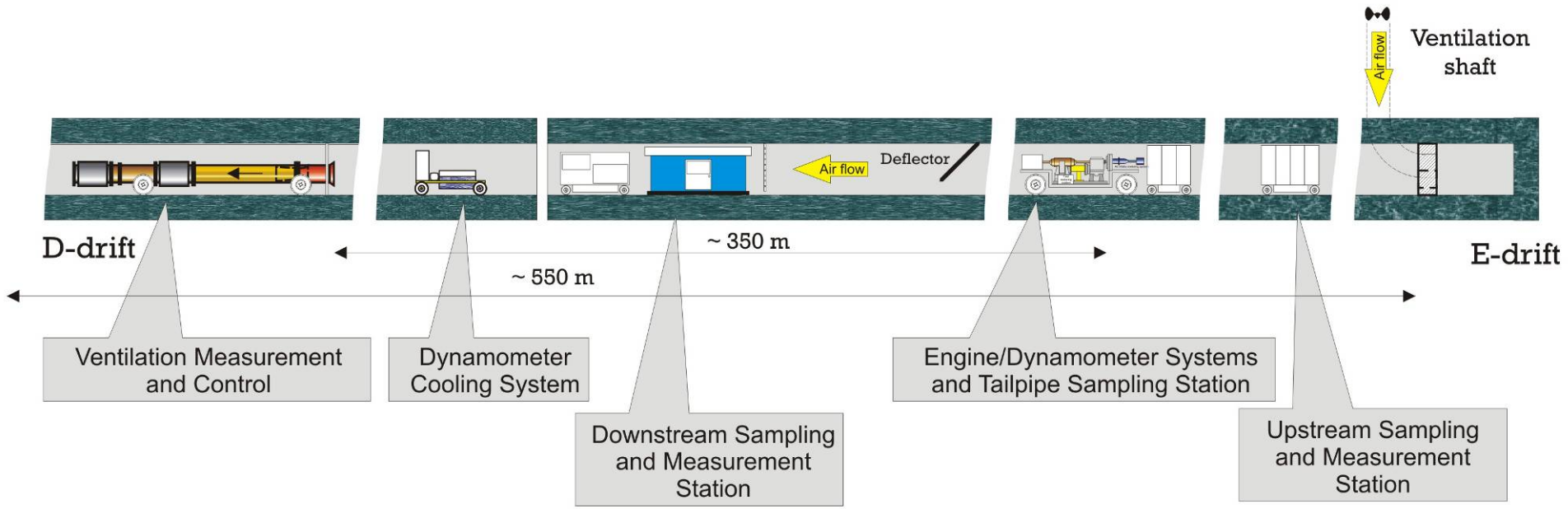
NIOSH is working to identify control technologies and strategies to reduce exposure of underground miners to diesel aerosols and gases.

- Evaluation of the effects of selected control technologies on diesel aerosols and gases in the workplace:
  - diesel particulate filters,
  - diesel catalytic converters,
  - disposable filter elements,
  - fuel formulations…
- Characterization of physical, chemical, and toxicological properties of aerosols emitted from engine equipped with DOC, DPF and DFE system and fueled with alternative fuels.
  - Solid vs. semi-volatile.
- Development of exposure assessment methodology and instrumentation.

NIOSH Diesel Laboratory at LLL



NIOSH Diesel Laboratory at LLL is unique laboratory that allow for evaluation of diesel emissions control technologies directly in underground environment.

- Compliment laboratory evaluations.
- Avoid laboratory uncertainties introduced with various simulations of processes.
- Bridge gap between inherently inaccurate field and unrealistic laboratory experiments.
- Collect representative samples for health studies.